Density dependence of meson - nucleon vertices in nuclear matter.

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Changes in the meson-nucleon coupling constant and the vertex form factor in nuclear matter are studied in a modified Skyrme Lagrangian including the σ-meson field that satisfies the scale invariance. Renormalization of g_A, the axial-vector coupling constant, and the nucleon mass are studied in a consistent model. The results are in good agreement with the empirical evidence. A calculation of the π-N commutator, Σ-term, indicates that the medium changes its magnitude considerably.

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I. INTRODUCTION

It is well established that in - medium nucleon - nucleon (N-N) cross sections manifest in heavy ion collisions need not to be the same as their free space values [1]. The origin of these changes must be reflected in modifications of the N-N interaction which is predominantly one-boson exchange. The parameters in meson exchange models are meson nucleon coupling constants and their masses. To avoid divergencies in loop integrals the meson - nucleon vertices are modified by form - factors which effectively provide cut-off parameters. All these parameters would change in the nuclear medium.

Even for the free N-N interaction the boson exchange models use a phenomenological ansatz for vertex form factors. Recently Holzwarth and Machleidt [2] have shown that among the QCD inspired pion - nucleon form factors the Skyrme form factor [3] is the most preferable: it can describe well both the pion - nucleon and nucleon - nucleon systems.

The purpose of the paper is to investigate the role of the medium in modifying the properties like meson nucleon coupling constant, meson-nucleon form factors and the axial vector form factor and the coupling constant. The calculations provide a consistent approach to modification of these properties in a modified Skyrme model that may be valid in a nuclear medium. The σ-meson is introduced as a dilaton field to satisfy scale invariance. Even though it is well known that scale invariance is badly broken, this provides a way to introduce the σ-meson which is so essential for an N-N interaction that is consistent with the two-body scattering data and the bound deuteron. In sections II and III the model will be presented; in section IV the strong vertex form factors are derived and in sections V and VI the renormalization of masses and coupling constants respectively will be discussed. The summary and discussion of the present approach are presented in the last section.

II. THE MODIFIED SKYRME LAGRANGIAN

In a previous paper [4] a medium modified Skyrme Lagrangian was proposed and applied to study the static properties of nucleons embedded in the nuclear medium. It gave a good description of changes in nucleon mass and its size in the medium. Here we shall outline

the basic features of the Langrangian and then extend it by including the dilated σ meson field in order to satisfy the scale invariance. It is well-known that scale invariance is badly broken, this symmetry is retained here to investigate its consequences.

Our basic assumption in modifying of the Skyrme Lagrangian [5]

$$\mathcal{L}_{\rm sk} = \frac{F_\pi^2}{16}{\rm Tr}\,(\partial_\mu U)(\partial^\mu U^+) + \frac{1}{32e^2}{\rm Tr}\,[U^+\partial_\mu U, U^+\partial_\nu U]^2 - \frac{F_\pi^2 m_\pi^2}{16}{\rm Tr}\,(U^+ - 1)(U - 1) \quad (2.1)$$

where F_π and e are the parameters of the model, was that, in the lowest order expansion of the chiral field $U = \exp(2i\vec{\tau}\vec{\pi}/F_\pi) \approx 1 + 2i(\vec{\tau}\vec{\pi})/F_\pi - 2\vec{\pi}^2/F_\pi^2 + \ldots$ the appropriate medium modified Skyrme Lagrangian $\mathcal{L}^*_{\rm sk}$ should give the well known equation for the pion field [6]:

$$\partial_\mu\partial^\mu\pi + (m_\pi^2 + \hat{\Pi})\pi = 0, \quad (2.2)$$

where m_π is the pion mass and $\hat{\Pi}$ is the self energy operator. This may be achieved simply by including $\hat{\Pi}$ in the pion mass term of the Skyrme Lagrangian:[1]

$$\mathcal{L}^*_{\chi{\rm sb}} = -\frac{F_\pi^2 m_\pi^2}{16}{\rm Tr}\,[(U^+ - 1)(1 + \hat{\Pi}/m_\pi^2)(U - 1)]. \quad (2.3)$$

In general, the operator $\hat{\Pi} = \hat{\Pi}_s + \hat{\Pi}_p$ in Eq. (2.3) acts both on the center of mass coordinate, R, and on the internal coordinate, $\vec{r}$, of the Skyrmion. Only homogenous nuclear matter is considered. The translational invariance of the medium and that of the basic Skyrme Lagrangian (2.1) makes the coordinate dependence of $\hat{\Pi}$ simpler: $\hat{\Pi} \equiv \hat{\Pi}(\vec{r} - \vec{R})$ which is also relevant for a moving Skyrmion. Further we assume that the Skyrmion is placed at the center of the nucleus i.e. $\vec{R} = 0$.

The P - wave part of the pion self energy $\hat{\Pi}_\Delta$ is dominated by the P_{33} resonance. A simple model used in practical calculations is the delta - hole model which concentrates on the pion - nucleon - delta interaction ignoring the nucleon particle - hole excitations. In momentum space the $\hat{\Pi}_\Delta$ is given by $\hat{\Pi}_p(\omega, \vec{k}) = \hat{\Pi}_\Delta(\omega, \vec{k}) = -\vec{k}^2\chi(\omega, \vec{k})/(1 + g'_0\chi(\omega, \vec{k}))$ [6] where $g'_0(= 0.6)$ is the Migdal parameter which accounts for the short range correlations, also known as the Ericson - Ericson - Lorentz - Lorenz effect. The pion susceptibility χ has nearly linear dependence on the nuclear density ρ:

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[1]Here and below the asterisk indicates the medium modified operators in quantities.

$$\chi(\omega,\vec{k}) \approx \frac{8}{9}\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2 \frac{\rho\omega_\Delta}{\omega_\Delta^2-\omega^2}\exp(-2\vec{k}^2/b^2), \tag{2.4}$$

where $f_{\pi N\Delta} \approx 2f_{\pi NN}$ ($f^2_{\pi NN}/4\pi \approx 0.08$) is the coupling constant, $\omega_\Delta \approx \vec{k}^2/2M_\Delta + M_\Delta - M_N$ and $b(\approx 7m_\pi)$ is the range of the vertex form factor that is chosen to have a gaussian form. For the pions bound in the nuclear matter ω is small $0 \le \omega \le m_\pi$, so in the lowest order $\hat{\Pi}_\Delta$ has the form:

$$\Pi_\Delta(\omega,\vec{k}) \approx -\vec{k}^2\chi_\Delta - \frac{\vec{k}^2\omega^2\alpha_{rt}}{\omega_\Delta^2}, \tag{2.5}$$

where $\chi_\Delta = 4\pi c_0\rho/(1+4\pi g'_0\rho)$, $\alpha_{rt} = \chi_\Delta/(1+4\pi g'_0 c_0\rho)$ and $c_0 = 8f^2_{\pi N\Delta}/9m^2_\pi 4\pi\omega_\Delta$. In the static case ($\omega \to 0$) it coincides with the Kisslinger optical potential [6] which was used in the previous paper [4].

Then in coordinate space the following symmetrized Lagrangian may be obtained

$$\begin{aligned}\mathcal{L}^*_{\rm sk} &= \frac{F^2_\pi}{16}{\rm Tr}\left(\frac{\partial U}{\partial t}\right)\left(\frac{\partial U^+}{\partial t}\right) - \frac{F^2_\pi}{16}(1-\chi_\Delta){\rm Tr}\,(\vec{\nabla}U^+)(\vec{\nabla}U) + \\ &+\frac{F^2_\pi}{16}\frac{\alpha_{rt}}{\omega^2_\Delta}{\rm Tr}\left(\frac{\partial}{\partial t}\frac{\partial U^+}{\partial r}\right)\left(\frac{\partial}{\partial t}\frac{\partial U}{\partial r}\right) + \frac{F^2_\pi m^{*2}_\pi}{16}{\rm Tr}\,(U+U^+-2) + \\ &+\frac{1}{32e^2}{\rm Tr}\,[U^+\partial_\mu U, U^+\partial_\nu U]^2,\end{aligned} \tag{2.6}$$

where $m^{*2}_\pi = {m_\pi}^2(1+\Pi_S(\rho)/{m_\pi}^2)$, the effective pion mass arises from the S - wave part of the self energy $\Pi_S(\rho)$. Since the operators in nuclear matter do not satisfy the Lorentz invariance there are two different effective coupling constants in the kinetic terms of Eq. (2.6)[2]. The third term with "mixed" derivative in the Lagrangian in Eq. (2.6) clearly vanishes in free space ($\alpha_{rt} = 0$ if $\rho = 0$) and contributes mainly to the moment of inertia, I, of the skyrmion. We shall consider this contribution in section V by estimating the NΔ mass splitting.

III. INCLUSION OF SCALAR MESON

Recently arguments have been given in favor of the empirical evidence for a scalar-isoscalar meson, σ. For example the isosinglet resonance with a mass $m_\sigma = 553.3 \pm 0.5$ MeV

[2]The similar second order derivative terms had been suggested in ref [7].

and width $\Gamma = 242.6 \pm 1.2 MeV$ [8] found in the recent $\pi\pi$ phase shift analyses is believed to have the properties of the σ meson that is essential for the N-N potential in OBE models to explain the NN-scattering data.

However the σ meson as a chiral partner of the pion was originally excluded from the Skyrme type Lagrangians. The only way of including σ meson in the Lagrangian is by means of a dilaton field appropriate to the scale transformations $x \to \lambda^{-1}x$. This may be achieved in the following way: Consider any term in the Lagrangian and multiply it by $\exp\{(d-4)\sigma\}$, with d the number of derivatives. In fact, since the scale invariance requires $\delta \int dx^4 \mathcal{L} = 0$, each term of the Lagrangian should have the scale dimension $\mathcal{D} = 4$. In this sense the scale dimension $\mathcal{D}$ has values of 3/2 and 1 for fermions and bosons respectively. In the Skyrme Lagrangian the scale dimension of the chiral field equals zero: $\mathcal{D}[U] = 0$ and hence $\mathcal{D}[\mathcal{L}_2] = 2$ and $\mathcal{D}[\mathcal{L}_4] = 4$ by itself. As to the pion mass term, $\mathcal{L}_{\chi \mathrm{sb}}$, its scale property is actually uncertain for its origin may be considered either as a quark - antiquark pair $\langle \bar{q}q \rangle$ with $\mathcal{D} = 3$ or a boson with $\mathcal{D} = 1$. The former is the most widely used one and this leads to the introduction of a factor $e^{-3\sigma}$ in the pion mass term i.e. $\mathcal{L}_{\chi \mathrm{sb}} \to \mathcal{L}_{\chi \mathrm{sb}} e^{-3\sigma}$.

The next step is the choice of the self interaction term $V(\sigma)$ of these dilaton fields. The choice $V(\sigma) = e^{-2\sigma}\Gamma_0^2(\partial_\mu\sigma)(\partial^\mu\sigma)/2 + C_g[e^{-4\sigma}(1+4\sigma) - 1]/4$ is commonly used and is uniquely determined by the trace anomaly of QCD [9]. However, the scalar meson, identified with fluctuations of the dilaton field associated here with the glueball, is too heavy to be considered as a sigma meson mentioned above. Its inclusion in the chiral Lagrangian has small effects on the nucleon properties even at finite densities [10]. The following choice

$$V(\sigma) = \frac{N_f F_\pi^2}{16} e^{-2\sigma}(\partial_\mu\sigma)(\partial^\mu\sigma) + \frac{N_f C_g}{48}\left[1 - e^{-4\sigma} - \frac{4}{\varepsilon}(1 - e^{-\varepsilon\sigma})\right], \tag{3.1}$$

where $\varepsilon = 8N_f/(33-2N_f)$, N_f is the number of flavors and C_g relates to the gluon condensate that associates the dilaton with a quarkonium which has a reasonable mass [11]. Although the dilaton quarkonium saturates only a part of the trace anomaly, namely the part which is produced by quark loops, but as part of the Skyrme Lagrangian it gives rather good description of the nucleon static properties [11] and the nucleon - nucleon interactions [12]. The mixing angle between the glueball and quarkonium fields was found to be small [11] and this is consistent with the QCD sum rules.

Now a skyrmion imbedded in nuclear matter is considered. When a dilaton field is introduced into the effective Lagrangian the dilaton potential $V(\sigma)$ would be modified by a σ field generated by the medium itself. While several attempts have been made [13], the correct nature of this modification is still poorly understood. On the other hand it is well known that the gluon condensate C_g as well as the quark condensate $\langle\bar{q}q\rangle$ decrease in the medium due to the partial restoration of the chiral symmetry. The present study is restricted to considering the medium modification of the dilaton potential (Eq. (3.1)) by taking into account mainly the change of C_g i.e. $C_g \to C_g^*$.

Thus putting all these considerations together the following Lagrangian is proposed for homogeneous nuclear medium in the static case

$$\mathcal{L}^*_{\rm sk} = \frac{F_\pi^2\alpha_p\chi^2}{16}{\rm Tr}\,\vec{L}_i^2 + \frac{1}{32e^2}{\rm Tr}\,[\vec{L}_i,\vec{L}_j]^2 + \frac{F_\pi^2 m_\pi^{*2}}{16}\chi^3{\rm Tr}\,(U+U^+-2) - \\ -\frac{F_\pi^2}{8}(\vec{\nabla}\chi)^2 + \frac{C_g^*}{24}\left[1-\chi^4-\frac{4}{\varepsilon}(1-\chi^\varepsilon)\right], \tag{3.2}$$

where $\chi(r) = e^{-\sigma(r)}$, $\alpha_p = 1-\chi_\Delta$, $\vec{L}_i = U^+\partial_i U$. Note that the Skyrme parameter e coupled to the fourth derivative term remains unchanged since this term is related to the exchange of a very heavy ρ - meson with mass $m_\rho^* = m_\rho \to \infty$ [14].

There may be two alternative approaches to applying this Lagrangian in nuclear physics. In QHD like models, the σ field plays the role of an external field modifying the properties of a soliton [13] or a bag [15] which moves in the background generated by the medium. In the present model this approach would mean that $\sigma \equiv \sigma(R)$ and $U \equiv U(r)$ [13] that makes the scale invariance doubtful. In contrast, the mean field approximation is not used for the σ field. Instead the σ-field is strongly coupled to the nonlinear pion fields so as to generate the soliton . We assume that $\sigma \equiv \sigma(r-R)$ and $U = U(r-R)$ are valid for a moving skyrmion. In the previous paper [4] a similar approximation (Eq. (3.2) with $\sigma = 0$) was used to estimate the medium modified static properties of the nucleon and found a well known behavior of the nucleon mass $M_N^*/M_N < 1$ and its size $R_N^*/R_N > 1$. In the next section we shall investigate in detail the dynamical properties of the meson - nucleon system.

IV. MESON - NUCLEON FORM FACTORS AND GOLDBERGER - TREIMAN RELATION

The semiclassical procedure for calculating the meson - nucleon vertex form - factors in a topological chiral effective Lagrangian [3] is well-known. In fact, the results of more accurate methods [16], based on the correct quantization of the fluctuating chiral fields nearly coincide with the original result that was given by Cohen [3]. Using the ansatz $U(\vec{r},t) = A(t)U_0(\vec{r} - \vec{R}(t))A^+(t)$ and defining the pion field as

$$\pi_\alpha(\vec{r}) = -\frac{iF_\pi}{4}\mathrm{Tr}\left[\tau_\alpha A U_0(\vec{r} - \vec{R})A^+\right] \tag{4.1}$$

the following expressions are obtained

$$\begin{aligned} G^*_{\pi NN}(q) &= \frac{4\pi M^*_N F_\pi \alpha_p(\vec{q}^{\,2} + m^{*2}_\pi/\alpha_p)}{3q}\int\limits_0^\infty j_1(qr)\sin(\Theta)r^2dr = \\ &= \frac{4\pi M^*_N F_\pi \alpha_p}{3}\int\limits_0^\infty \frac{j_1(qr)}{qr}S_\pi(r)r^3dr \end{aligned} \tag{4.2}$$

for the pion nucleon form factor and

$$G^*_{\sigma NN}(q) = 2\pi F_\pi(\vec{q}^{\,2} + m^{*2}_\sigma)\int\limits_0^\infty j_0(qr)\sigma(r)r^2dr = 2\pi F_\pi\int\limits_0^\infty j_0(qr)S_\sigma(r)dr \tag{4.3}$$

for the sigma nucleon form factor respectively. The details and the explicit expressions for the source functions $S_\pi(r)$ and $S_\sigma(r)$ are given in the Appendix. Here we note that, in the chiral soliton models formulas for meson nucleon form - factors are mainly determined by the quantization scheme rather than by details of the Lagrangian. The latter manifests itself through equations of motion whose solutions $\Theta(r)$ and $\sigma(r)$ with spherically symmetric ansatz are $U_0 = \exp(i\vec{\tau}\vec{n}\Theta(r))$, $\vec{n} = \vec{r}/r$, and $\sigma(\vec{r}) \equiv \sigma(r)$ that should be used in Eqs (4.2), and (4.3). The effective mass of the nucleon M^*_N is given by

$$M^*_N = M^*_H + \frac{3}{8I^*} \tag{4.4}$$

where M^*_H is the mass of the classical hedgehog soliton and I^* is the moment of inertia of the spinning mode.

The effective pion decay constant f^*_π should be understood before considering the Goldberger - Treiman (GT) relation. Medium renormalized pion - decay constant f^*_π can be naturally defined by the PCAC relation:

$$\vec{\nabla}\vec{A}_\alpha(x) = f_\pi^* m_\pi^{*2}\pi_\alpha(x) \tag{4.5}$$

The medium modified axial coupling constant g_A^* measures the spin - isospin correlations in a nucleon, embedded in a medium and is defined as the expectation value of the space component of the axial current A_α^i in the nucleon state at zero momentum transfer [5]:

$$\lim_{q\to 0}\langle N(\vec{P}')|A_\alpha^i(r)|N(\vec{P})\rangle = \frac{2}{3}\lim_{q\to 0} G_A^*(\vec{q}^{\,2})\langle N|\frac{\sigma_i\tau^\alpha}{2}|N\rangle \exp(i\vec{q}\vec{r}) \tag{4.6}$$

where $\vec{q} = (\vec{P}' - \vec{P})$ and $G_A^*(\vec{q}^{\,2})$ is the axial form factor of nucleon, $G_A^*(0) = g_A^*$. Here σ_i is the component of the nucleon spin. Due to the semiclassical quantization prescription, Eq. (4.1), the matrix element of the pion field evaluated between nucleon states is given by:

$$\langle N(P')|\pi_\alpha(\vec{r} - \vec{R})|N(P)\rangle = \frac{F_\pi \exp{(i\vec{q}\vec{r})}}{6}\int \langle N|\sigma_\alpha(\vec{\tau}\hat{x})|N\rangle e^{-i\vec{q}\vec{x}}\sin(\Theta)d\vec{x} \tag{4.7}$$

Evaluation of the matrix elements between nucleon states for both sides of Eq. (4.5) yields

$$g_A^* = \frac{4\pi F_\pi f_\pi^* m_\pi^{*2}}{9}\int_0^\infty \sin(\Theta) r^3 dr \tag{4.8}$$

that was originally derived in [17] for the free particle. By comparing this equation with the expression for pion nucleon coupling constant: $g_{\pi NN}^* = G_{\pi NN}^*(q^2)|_{q=0}$ given by Eq. (4.2) the following medium modified Goldberger - Treiman relation is realized

$$g_{\pi NN}^* f_\pi^* = g_A^* M_N^* \quad . \tag{4.9}$$

This relation has been proved [10,18]. On the other hand g_A^* and the axial form factor $G_A(q^2)$ may be calculated directly from the Lagrangian in Eq. (3.2) in terms of the Noether currents [5]. This gives

$$G_A(q^2) = -4\pi\int_0^\infty [j_0(qr)A_1(r) + \frac{j_1(qr)}{qr}A_2(r)]r^2 dr,$$

with

$$\begin{aligned} A_1(r) &= \frac{s_2}{8r}\left[e^{-2\sigma}\alpha_p F_\pi^2 + \frac{4}{e^2}\left(\Theta'^2 + d\right)\right], \\ A_2(r) &= -A_1(r) + \frac{\Theta'}{4}\left(F_\pi^2\alpha_p e^{-2\sigma} + \frac{8d}{e^2}\right) \end{aligned} \tag{4.10}$$

and

$$g_A^* = -\frac{\pi}{3}\int_0^\infty \left\{ e^{-2\sigma(r)} F_\pi^2 \alpha_p \left(\Theta' + \frac{s_2}{r}\right) + \frac{4}{e^2}\left[(\Theta'^2 + d)\frac{s_2}{r} + 2\Theta' d\right]\right\} r^2 dr \tag{4.11}$$

where $d = \sin^2(\Theta)/r^2$, $s_2 = \sin(2\Theta)$, and α_p is defined in Eq. (3.2). The renormalized pion decay constant f_π^* is obtained by combining the results given in Eq.s (4.9) and (4.11).

V. RENORMALIZATION OF HADRON MASSES

Before going to a quantitative analyses of the medium effects we fix the following set of parameters for free space: $F_\pi = 186MeV$, $m_\pi = 139MeV$, $C_g = (260MeV)^4$. This gives a good description of the sigma meson properties $m_\sigma = 550MeV$, $\Gamma_\sigma = 251.2MeV$, that may be compared with their experimental values obtained from the recent $\pi\pi$ phase shift analysis [8]. The Skyrme parameter e has been adjusted to reproduce the pion nucleon coupling constant: $g_{\pi NN} = 13.5$ for $e = 4.05$. The well-established fixed parameters of the P - wave pion self energy in Eq. (2.5) are used in the pion sector: $g_0' = 0.6$, $c_0 = 0.13 m_\pi^{-3}$ [4,6].

Now, the medium dependence of the input parameters may be considered. The possible renormalization of the Skyrme parameter e cannot be studied in the present approach unless the ρ meson is included in the Lagrangian explicitly. So we take $e^* = e$.

We adopt the following parametrization of m_π^*

$$m_\pi^* = m_\pi \sqrt{1 + \hat{\Pi}_s(\rho)/m_\pi^2} = m_\pi \sqrt{1 - 4\pi b_0 \rho \eta / m_\pi^2}\ , \tag{5.1}$$

where $\eta = 1 + m_\pi/M_N$ and b_0 is an effective S - wave $\pi - N$ scattering length. It is anticipated [4] that the results will not be to sensitive to the value of b_0.

The only input parameter in the scalar meson sector is C_g^*. The medium renormalization of the gluon condensate C_g^*, in contrast with the renormalization of the quark condensate $\langle \bar{q} q \rangle$ [19] and meson masses [20], is poorly known. However in the present approach (3.2) C_g^* may be determined by m_σ^* through the equation

$$C_g^* = \frac{3 F_\pi^2 m_\sigma^{*2} N_f}{4(4 - \varepsilon)}. \tag{5.2}$$

Various approaches [10,15,18] show that m_σ^*, has a linear density dependence. The following parametrization

$$\frac{m_\sigma^*}{m_\sigma} = 1 - 0.12\frac{\rho}{\rho_0} \tag{5.3}$$

is adopted here. It is consistent with the one obtained in the QCM framework [15].

The results for the static properties of hadrons are presented in Table I. The second (m_π^*) and the third (m_σ^*) columns of the table should be considered as input data for they were taken from other models [6,15]. The medium renormalized gluon condensate C_g^* is calculated from Eq.s (5.2) and (5.3) with $N_f = 2$. The change in the gluon condensate is small $\sim 5\%$ at normal nuclear matter density, $\rho_0 = 0.5 m_\pi^3$. The stiffness of the gluon condensate as a consequence of the lack of scale invariance of QCD has been shown by Cohen [21] who found that the fourth root of the condensate might be altered by no more than 4% [19].

The main contribution to the $\sigma\pi\pi$ vertex, and hence, to the decay width of σ meson at the tree level: $\Gamma_{\sigma\to\pi\pi} = m_\pi^{*3} x^3 \alpha_p^2 \sqrt{1-4x^2}(1-2x^2)^2/4\pi F_\pi^2$, where $x = m_\pi^*/m_\sigma^*$, arises from the first term of the Lagrangian in Eq. (3.2). The table shows that the width $\Gamma_{\sigma\to\pi\pi}$ is decreased significantly in the medium. This stimulates an interest to observe the σ mesons in nuclei by experiments proposed earlier [22].

Now medium effects on the mass of nucleon M_N^* and $N\Delta$ mass splitting $\delta M_{N\Delta} = M_\Delta^* - M_N^*$ will be considered. In general, it is almost impossible to reproduce simultaneously the experimental values of masses and coupling constants within the Skyrme model even for a free particle. Since dynamics is the main interest, the set of parameters was chosen so as to reproduce the pion nucleon coupling constant: $g_{\pi NN} = 13.5$. It is clear from Table I that the free space value of the nucleon mass M_N is slightly large $M_N = 1413 MeV$, whereas $\delta M_{N\Delta}$ is reproduced rather well $\delta M_{N\Delta} = 284 MeV$ ($\delta M_{N\Delta}^{\rm exp} = 293 MeV$). The effective mass of the nucleon M_N^* in normal nuclear matter density is decreased by a factor of $M_N^*/M_N = 0.82$ which is in a good agreement with the estimates based on QCD sum rules $M_N^*(QCD) = 680 \pm 80 MeV$ i.e. $M_N^*/M_N = 0.72 \pm 0.09$ [23]. We underline that the mass of the nucleon should be treated as the mass of the baryon which emerges as a soliton in the sector with baryon number one (B=1).

The study of $N\Delta$ mass splitting gives a chance to estimate the contribution from the "mixed derivative" term - the third term on the r.h.s of Eq. (2.6):

$$\mathcal{L}_{rt} = \frac{F_\pi^2}{16}\frac{\alpha_{rt}}{\omega_\Delta^2}\mathrm{Tr}\left(\frac{\partial}{\partial t}\frac{\partial U^+}{\partial r}\right)\left(\frac{\partial}{\partial t}\frac{\partial U}{\partial r}\right). \tag{5.4}$$

Actually, owing to the canonical quantization $\delta M_{N\Delta}$ is related to the moment of inertia I by: $\delta M_{N\Delta} = M_\Delta^* - M_N^* = 3/2(I_0^* + I_{rt})$, where I_{rt} is the net contribution from $\mathcal{L}_{rt}$ (clearly $I_{rt} = 0$ in free space). The explicit expressions for I_0^* and I_{rt} are given in the Appendix. In Table I are shown $\delta M_{N\Delta}$ that has been calculated with the inclusion of I_{rt} (denoted here $\delta M_{N\Delta}^a$) and without the inclusion of $I_{rt}(\delta M_{N\Delta}^b)$. In the nuclear medium the $\mathcal{L}_{rt}$ term leads to an enhancement of the moment of inertia decreasing $\delta M_{N\Delta}$ significantly. Even without the term $\mathcal{L}_{rt}$ in the lagrangian the shift of $\delta M_{N\Delta}$ from its free value $\delta M_{N\Delta}^*/\delta M_{N\Delta} = 0.75$ is larger than that obtained by Meissner [10] in a medium modified chiral soliton model based on the Brown Rho (BR) scaling law ($\delta M_{N\Delta}^*/\delta M_{N\Delta} = 0.87$).

VI. RENORMALIZATION OF COUPLING CONSTANTS AND FORM - FACTORS

The axial - vector exchange currents must be considered in order to investigate the medium effects on g_A and on the axial form factor $G_A(q^2)$. However it is known that the bulk of exchange current effects arise from the $\triangle$-hole contributions. Including such $\triangle$-h effects would imply that bulk of the exchange currents effects are included in the effective g_A. In a heavy nucleus it is meaningful to take these axial exchange operators into account as corrections to the effective axial current operator of a single nucleon $\vec{A}_\alpha = -g_A^*\vec{\sigma}\vec{\tau}_\alpha$. So g_A^* in Eq. (4.11) may be considered as an effective axial coupling constant modified by the medium polarization and screening effects since we are considering an effective one body problem of a nucleon embedded in the nuclear medium.

The second column of Table II displays a well known quenching behavior of g_A that is mainly caused by a factor $\alpha_p = 1 - \chi_\Delta < 1$ in the first term of Eq. (3.2). Note that the same set of input parameters F_π, e, c_0 (but without dilaton field $\sigma = 0$) gives the desired ratio $g_A^*/g_A = 0.8$ [4]. The present calculations show that the inclusion of the scalar meson, which induces an additional attraction, prevents larger quenching: $g_A^*/g_A = 0.9$.

In nuclei, a nucleon polarizes the medium in its vicinity. This leads to a screening

effect that reduces the effective pion nucleon coupling strength. In the present approach the screening mechanism may be described as being due to virtual Δh excitations that have been taken into account by the self - energy $\hat{\Pi}_\Delta$ term in Eq. (2.5). At normal nuclear matter density the renormalization of $g_{\pi NN}$ amounts to a reduction of 25% of the coupling strength. This is sufficient to explain the quenching of the Gamov - Teller strength in heavy nuclei [24]. Furthermore this is consistent with a general argument based on Ward-Takahashi relations [25].

The effective pion decay constant f_π^* is obtained by using the GT relation (4.9). Comparing the ratios f_π^*/f_π (Table II) and M_N^*/M_N (Table I) one may see that they both decrease in the nuclear medium. This fact is in good qualitative agreement with Brown-Rho scaling law [26] predicted within a simple Skyrme model.

The masses of w- and σ-meson are supposed to decrease by the scaling law. There are experimental indications that this is true. In the same way the σN coupling constant is expected to decrease. The ratio of $g_{\sigma NN}^*$ to its free value is presented in Table II. The changes in $g_{\pi NN}$ and $g_{\sigma NN}$ are nearly the same. Both are reduced in the medium by $\approx 25\%$ at $\rho = \rho_0$.

In Figs 1 and 2, the renormalized πNN and σNN vertex form factors respectively at $\rho = \rho_0$ (dashed lines) in comparison with these in the free space (solid lines) are displayed. Appreciable quenching of both form factors is observed. At small momentum transfer these can be parametrized by a monopole form i.e. $G_{\pi NN}(\vec{q}^{\,2}) = g_{\pi NN}/(1 + \vec{q}^{\,2}/\Lambda_\pi^2)$ and $G_{\sigma NN}(\vec{q}^{\,2}) = g_{\sigma NN}/(1 + \vec{q}^{\,2}/\Lambda_\sigma^2)$. Table II shows that the cut off parameter Λ_π is decreased significantly at $\rho = \rho_0$. Relatively small changes in $G_{\sigma NN}(\vec{q}^{\,2})$ seem to be caused by a stiffness of the σ-field or equivalently C_g^* [19].

The nucleon axial form factor $G_A(\vec{q}^{\,2})/G_A(0)$calculated for $\rho = 0$ and $\rho = \rho_0$ is presented in Fig. 3 with solid and dashed curves respectively. It is seen that, the modification of $G_A(\vec{q}^{\,2})$ is not as simple as that of $G_{\pi NN}(\vec{q}^{\,2})$. The medium leads to a quenching of the meson nucleon form factors over a range of $\vec{q}^{\,2}$, while the quenching of $G_A(\vec{q}^{\,2})$ takes place at $\vec{q}^{\,2} = 0$ and $\vec{q}^2 > 10 fm^{-2}$.

A further interesting quantity is the pion-nucleon sigma term $\Sigma_{\pi N}$. It is both the chiral

symmetry breaking piece of the nucleon mass and a measure of the scalar density of quarks inside the nucleon. Due to the Hellman Feynman theorem, it is easily calculated [28] in the Skyrme model

$$\Sigma_{\pi N} = m_q \frac{\partial M_N}{\partial m_q} = \frac{\partial M_N}{\partial m_\pi^2} m_\pi^2. \tag{6.1}$$

For free space ($\rho = 0$) the lagrangian including scalar mesons Eq.(3.2) gives $\Sigma_{\pi N} \approx 20.1 MeV$ that is much smaller than that obtained in the original skyrme model [5]. It may be argued that $\Sigma_{\pi N}$ may also undergo changes in the nuclear medium i.e. $\Sigma^*_{\pi N} \neq \Sigma_{\pi N}$. Actually, PCAC allows us to relate $\Sigma_{\pi N}$ to the soft-pion limit of πN scattering [29] whose parameters may not be the same in free space and the medium. So, defining an effective value of the in-medium pion-nucleon sigma commutator as

$$\Sigma^*_{\pi N} = m\ {}^*\langle N| \int d\vec{r} \bar{\psi}\psi |N\rangle^* = \frac{\partial {M_N}^*}{\partial m_\pi^{*2}} m_\pi^{*2} \tag{6.2}$$

where $|N\rangle^*$ is the state of the nucleon bound in nuclear matter, we obtain $\Sigma^*_{\pi N} \approx 40.1 MeV$ at normal nuclear density. This means a large increase of the nucleon sigma term: $\Sigma^*_{\pi N}/\Sigma_{\pi N} \approx 2$. Using appropriate solutions of Eqs. (A.8), it is estimated that

$$\frac{\Sigma^*_{\pi N}}{\Sigma_{\pi N}} \approx \frac{m_\pi^{*2} \int_0^\infty e^{-3\sigma^*}[1-\cos(\Theta^*)]x^2 dx}{m_\pi^2 \int_0^\infty e^{-3\sigma}[1-\cos(\Theta)]x^2 dx} = 1.88 \frac{m_\pi^{*2}}{m_\pi^2}\ , \tag{6.3}$$

where $\sigma^*(x)$, $\Theta^*(x)$ are profile functions at $\rho = \rho_0$ and $\sigma(x)$, $\Theta(x)$ are those at $\rho = 0$. Thus, the medium renormalization of $\sum_{\pi N}$ is caused mainly due to a large modification of the profile functions (see Figs. 4a, 4b). On the other hand $\Sigma_{\pi N}$ gives a good estimate for the quark condensate at finite density:

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_{vac}} = 1 - \frac{\Sigma^*_{\pi N}\rho}{{m_\pi}^2 f_\pi^2} \tag{6.4}$$

Hence, assuming the last equation holds it is concluded that the in medium enhancement of $\Sigma_{\pi N}$ leads to further quenching of the scalar density of quarks $\langle \bar{q}q \rangle_\rho$ in nuclear matter.

VII. DISCUSSIONS AND SUMMARY

We have proposed a medium modified Skyrme like Lagrangian which takes into account the distortion of the basic nonlinear meson fields by the nuclear medium. It is extended by including the scalar - isoscalar sigma meson which is identified with a dilaton - quarkonium. The influence of the medium on pion fields is introduced by the self energy operators $\hat{\Pi}_p, (= \hat{\Pi}_\Delta)$ and $\hat{\Pi}_s$ while the effect of the medium on the dilaton field is limited to the renormalization of the gluon condensate. The Lagrangian is applied to study changes in the hadron masses and meson - nucleon vertex form - factors.

In particular, the mass of the Δ - resonance decreases more than that of the nucleon in the nuclear medium. Consequently the pion requires lesser energy to excite the nucleon to the Δ in the nuclear medium than it does for a free nucleon. The mass difference between Δ and N decreases to 42% of that for free particles at the nuclear matter density. This is quite consistent with earlier estimates [30,10] but contradicts the recent theoretical results of Mukhopadhyay and Vento [31], who found $\delta M^*_{N\Delta}/\delta M_{N\Delta} \approx 1.25$ for $\rho = 0.8\rho_0$. So, it would be quite interesting to study NΔ mass splitting experimentally by an analyses of the NΔ transitions in heavy nuclei.

We have investigated the characteristic changes of the decay width $\Gamma_{\sigma\to\pi\pi}$ at zero temperature. One may expect that the temperature-dependence of the physical quantities is qualitatively similar to the ρ dependence. In this sense, our results are in good agreement with predictions of the in - medium NJL model [32], that at sufficiently high temperatures the σ meson becomes a sharp resonance and its width may even vanish. Clearly, more precise predictions on $\Gamma_{\sigma\to\pi\pi}(T,\rho)$ in the framework of the present Lagrangian should be made by studying thermal Green's function of σ - meson e.g. within Thermo Field Dynamics.

Furthermore the in - medium version of GT relation (4.9) holds in the present approach. The renormalized pion decay constant f^*_π and nucleon mass M^*_N do not satisfy the BR scaling [18]: the change in the nucleon mass is larger than that in f_π.

The medium effects lead to a quenching of the meson - nucleon form factors as well as the coupling constants $g_{\pi NN}$ and $g_{\sigma NN}$. The latter should be compared with the results of Banerjee and Tjon [33] obtained in the framework of CCM. There $g_{\sigma NN}$ and $g_{\pi NN}$ increased

at low densities while in the present approach and in QCM [15] they decrease with density.

What is the possible origin of this descrepancy.Possible in - medium changes in nucleon properties and in meson - nucleon dynamics should be understood within those effective field thories where a nucleon has an internal structure. In general the models on which they are based differ even at the single nucleon level.Moreover these models may be radically different from one another at a deeper level such as the confinement mechanism for quarks or a realization of the chiral invariance. For example, one may easily find that there is no confinement in the Skyrme model by construction while it is implemented in CCM [33] more carefully than in QCM. Now it is natural to propose that these differences are reflected not only in the free space but also in the case when the nucleon, and hence quarks, are influenced by the medium. It maybe concluded that all "starred" features of nucleon (mass, copuling constants etc) are model dependent and, comparing the present model with the CCM model of Banerjee and Tjon or QCM may not be entirely straight forward.

However we believe that the natural reduction of the meson masses and coupling strengths found in the present model are expected to give a good description of the saturation properties of nuclear matter. It would be interesting to calculate properties of finite nuclei and nuclear matter at normal and high density to establish the validity of the model. The heavy ion reactions would possibly open a new window at finite temperature properties of nucleons in nuclei and other nuclear properties. In particular a study of the change of the effective mass and coupling constants with temperature would shed new light on the type of effective Lagrangian that is appropriate for the system.

By introducing a formal definition of the in - medium pion - nucleon sigma term $\Sigma^*_{\pi N} = m^{*2}_\pi[\partial {M_N}^*/\partial m^{*2}_\pi]$, it is found that in contrast to the meson - nucleon coupling strengths the $\Sigma_{\pi N}$ increased in the medium: $\Sigma^*_{\pi N}/\Sigma_{\pi N} \approx 2$. This enhancement could lead to a decrease of the quark condensate $\langle \bar{q}q \rangle_\rho$ in nuclear matter. However as it was recently pointed out by Birse [34] this change should not lead to a drastic and rapid restoration of the chiral symmetry in nuclear matter.

It is anticipated that forthcoming ultrarelativistic heavy - ion collision experiments (e.g. at RHIC) will provide significant new information on the strong interactions through the

detection of changes in hadronic properties [35]. This would provide an impetus to consider refined models for strong interactions in nuclear matter at high density and at finite temperature.

It is useful to comment on the role of the scale invariance in nuclear physics and its breaking by the trace anomaly. The physical scalar - isoscalar sigma meson has been considered here as a dilaton - quarkonium rather than a heavy quarkonium which is used in standard approaches [9].In a more general case a heavy scalar gluonium and light scalar quarkonium are both needed to saturate the low energy theorems involving the trace anomaly of energy-momentum tensor. Fortunately, it was shown [36] that the heavy gluonium degree of freedom can be integrated out, so that the contribution from the light quarkonium becomes effectively larger (i.e. dominates). In this sense the approach given by eq. (3.1) is similiar to the one used in [36] [1], although in the latter case the dilaton quarkonium has an anomalous scale dimension i.e.

$$\mathcal{D}_{\rm an} = \mathcal{D}_\sigma - 1 \neq 0.$$

Actual calculations in the framework of a chiral effective lagrangian for nuclei with structureless nucleons predicted rather large value :$\mathcal{D}_{\rm an} \approx 5/3$, or in general $\mathcal{D}_{\rm an} > 1$, otherwise bulk properties of finite nuclei cannot be reproduced. On the other hand, one may ask here, how a model with such a large anomalous dimension of scalar quarkonium would describe properties of a single nucleon in free space? This question may be answered by including the dilaton quarkonium with $\mathcal{D}_{\rm an} \neq 0$ into the Skyrme model or into the chiral soliton model [37] by means of scale invariance and trace anomaly. This work is in progress.

In conclusion the modified Skyrme Lagrangian with scale invariance provides a useful insight into the role of medium in changing various properties of the mesons and nucleons. Even though scale invariance is badly broken in strong interactions its inclusion gives important information on the role of this symmetry property in a many-particle system.

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APPENDIX

The expressions for $G^*_{\pi NN}(q^2)$ and $G^*_{\pi NN}(q^2)$ are derived following the method given by Cohen [3]. The small fluctuations around the vacuum value are related to the pion field by $U = \exp(2i\vec{\tau}\vec{\pi}/F_\pi) \approx 1 + 2i\vec{\tau}\vec{\pi}/F_\pi - 2\vec{\pi}^2/F_\pi^2 + \ldots$ which gives the following approximation for the Lagrangian in Eq. (3.2): $\mathcal{L} \approx -\frac{1}{2}(\vec{\nabla}\vec{\pi})^2\alpha_p - \frac{1}{2}m_\pi^{*2}\vec{\pi}^2$ and for the equation of motion: $-(\vec{\nabla}^2\pi)\alpha_p + m_\pi^{*2}\vec{\pi} = 0$. The factor $\alpha_p = 1 - \chi_\Delta$ in the last equations is obtained by renormalization of the pion propagator in the medium i.e. by the Δ - hole self energy term $\hat{\Pi}_\Delta$. We define the in-medium πNN coupling constant and the vertex form factor by introducing the source term $\vec{j} = iG^*_{\pi NN}\bar{\psi}\vec{\tau}\gamma_5\psi$ into the equation of motion:

$$-\nabla^2\vec{\pi}\alpha_p + m_\pi^{*2}\vec{\pi} = iG^*_{\pi NN}\bar{\psi}\gamma_5\vec{\tau}\psi, \tag{A.1}$$

where

$$\psi|N(\vec{P})\rangle = \frac{e^{i\vec{P}\vec{x}}}{(2\pi)^{3/2}}\left(\frac{E^* + M_N^*}{2E^*}\right)^{1/2}\begin{pmatrix} 1 \\ (\vec{\sigma}\vec{P})/(E^* + M_N^*) \end{pmatrix}\chi_S, \tag{A.2}$$

where $E^{*2} = \vec{P}^2 + M^{*2}$. In the Breit frame ($\vec{P}' = -\vec{P}$, $\vec{q} = \vec{P} - \vec{P}'$) the matrix element of the source evaluated between nucleon states is given by:

$$\langle N(\vec{P}')|\vec{j}(r)|N(\vec{P})\rangle = \frac{e^{i\vec{q}\vec{r}}\langle N|(\vec{\sigma}\vec{q})\ \vec{\tau}|N\rangle}{(2\pi)^3\ \ 2M_N^*}. \tag{A.3}$$

Using the quantization rules

$$\pi_\alpha(r) = -\frac{iF_\pi}{4}\mathrm{Tr}\,[\tau_\alpha A U_0(r-R)A^+],$$

$$\langle N|\mathrm{Tr}\,\tau_\alpha A\tau_\beta A^+|N\rangle = -\frac{2}{3}\langle N|\sigma_\alpha\tau_\beta|N\rangle \tag{A.4}$$

we have

$$\langle N'(\vec{P}')|\pi_\alpha(\vec{r},\vec{R})|N(\vec{P})\rangle = \frac{e^{i\vec{q}\,\vec{r}}}{(2\pi)^3}\int\langle N'|\pi_\alpha(x)|N\rangle e^{-i\vec{q}\,\vec{x}}d\vec{x} = \\ = \frac{F_\pi e^{i\vec{q}\,\vec{r}}}{6(2\pi)^3}\int\langle N'|\sigma_\alpha(\vec{\tau}\vec{x})|N\rangle e^{-i\vec{q}\,\vec{x}}\sin(\Theta)d\vec{x} \tag{A.5}$$

where Θ is defined by the hedgehog ansatz $U_0(r) = e^{i(\vec{\tau}\vec{r})\Theta(r)}$. Now the matrix element of Eq. (A.1) is evaluated between collective wave functions for spin-up proton $|p\uparrow\rangle$ with momentum $\vec{P}$ and $\vec{P}'$ in the Breit frame and using equations (A.2) - (A.5) to obtain

$$G^*_{\pi NN}(\vec{q}^{\,2}) = -\frac{iF_\pi\alpha_p M^*_N}{3q}\int(-\nabla^2 + m^{*2}_\pi/\alpha_p)\hat{x}_3\sin(\Theta)e^{-i\vec{q}\,\vec{x}}d\vec{x} = \\ = \frac{4\pi F_\pi\alpha_p M^*_N}{3}\int_o^\infty \frac{j_1(qx)}{qx}S_\pi(x)x^3dx \tag{A.6}$$

where $S_\pi(x) = -2\Theta' c/x - \Theta'' c + \Theta' s + 2s/x^2 + m^{*2}_\pi s/\alpha_p$ with $c = \cos(\Theta)$, $s = \sin(\Theta)$.

Similarly, the coupling constant at the σNN vertex is defined by the equation: $(-\vec{\nabla}^2 + m^{*2}_\sigma)\sigma = G^*_{\sigma NN}\bar{\psi}\psi$. Evaluating matrix elements of both sides of this equation it is easy to obtain the σNN form factor:

$$G^*_{\sigma NN}(\vec{q}^{\,2}) = 2\pi F_\pi\int_o^\infty j_0(qx)S_\sigma(x)dx\ , \tag{A.7}$$

with $S_\sigma(x) = -x^2\sigma'' + 2x\sigma' + x^2 m^{*2}_\sigma\sigma$.

Note that the profile functions $\Theta(r)$ and $\sigma(r)$ in $S_\pi(x)$ and $S_\sigma(x)$ are the solutions of the equations of motion:

$$\begin{aligned}
&\Theta'' x^2\chi^2\alpha_p + 4s_2\Theta'^2 + 8s^2\Theta'' + 2x\Theta'\chi^2\alpha_p + 2x^2\Theta'\chi\chi'\alpha_p - \\
&\qquad -\chi^2\alpha_p s_2 - 4s_2 d - x^2\beta^2\chi^3 s = 0 \\
&x^2\chi'' + 2\chi\chi' - 2\chi\alpha_p x^2(\Theta'^2/2 + d) - 16x^2\mathcal{D}_{eff}(\chi^3 - \chi^{\varepsilon-1}) - \\
&\qquad -3x^2\beta^2(1-c)\chi^2 = 0.
\end{aligned} \tag{A.8}$$

where $x \equiv eF_\pi r$, $s_2 \equiv \sin(2\Theta)$, $d \equiv s^2/x^2$, $\beta = m^*_\pi/eF_\pi$, $\mathcal{D}_{eff} = C^*_g/24e^2F^4_\pi$, $\chi \equiv \exp(-\sigma(x))$. The boundary conditions are:
$\Theta = \pi$, $\sigma' = 0$ for $x \to 0$ and $\Theta \sim (1+\beta x)e^{-\beta x}/x^2$, $\sigma \sim \Theta^2$ for large x.

For completeness we write also the explicit expressions for $I = I_0^* + I_{rt}$:

$$I_0^* = \frac{2\pi}{3e^3F_\pi}\int_0^\infty s^2\{e^{-2\sigma} + 4(\Theta'^2 + d)\}x^2dx, \qquad I_{rt} = \frac{\pi\alpha_{rt}}{3\omega_\Delta^2 eF_\pi}\int_0^\infty \{\Theta'^2c^2 + 2d\}x^2dx.$$

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FIGURE CAPTIONS

Fig. 1. The πNN form factor.The solid and dashed curves give results for the free space ($\rho = 0$) and the nuclear matter ($\rho = \rho_0$) respectively.

Fig. 2. The σNN form factor. Solid and dashed curves are for $\rho = 0$ and $\rho = \rho_0$ respectively.

Fig. 3. The axial form factor. Solid and dashed curves are for $\rho = 0$ and $\rho = \rho_0$ respectively.

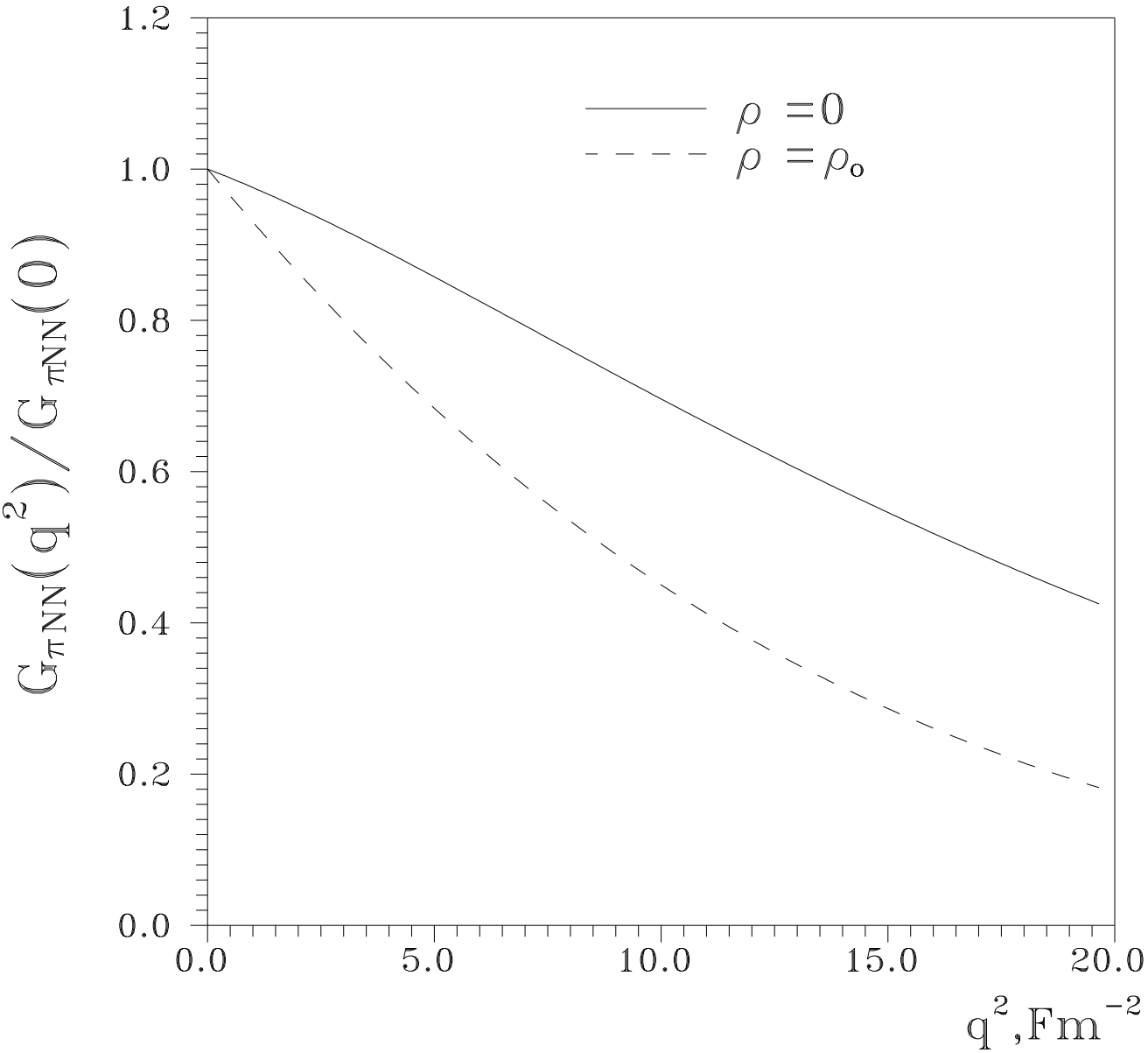
Fig. 4. The profile functions $\Theta(r)$ (Fig. 4a.) and $\sigma(r)$ (Fig. 4b.) for the $\rho = 0$ (solid curve) and $\rho = \rho_0$ (dashed curve). They are the solutions of equations of motion (A.8) in the sector with $B = 1$.

TABLE I. Density dependence of hadrons properties. All quantities are in MeV.

ρ/ρ_0	m_π^*	m_σ^*	$(C_g^*)^{1/4}$	M_N^*	$\Gamma^*_{\sigma\to\pi\pi}$	$\delta M^a_{N\Delta}$	$\delta M^b_{N\Delta}$
0.0	139.00	550.1	260.70	1413	251.2	283.7	283.7
0.5	144.90	513.8	251.06	1271	88.7	200.1	238.1
1.0	149.06	493.8	246.12	1157	34.6	161.9	205.4

TABLE II. Coupling constants and cut-off parameters at finite density. (All values are normalized to their free space ones.)

ρ/ρ_0	g_A^*/g_A	$g^*_{\pi NN}/g_{\pi NN}$	$g^*_{\sigma NN}/g_{\sigma NN}$	f_π^*/f_π	$\Lambda_\pi^*/\Lambda_\pi$	$\Lambda_\sigma^*/\Lambda_\sigma$	r_a^*/r_a
0.5	0.96	0.91	0.88	0.98	0.70	0.90	0.93
1.0	0.92	0.80	0.78	0.94	0.56	0.84	0.55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0.6
0.4
0.2
0.0
0.0
5.0
10.0
15.0
20.0
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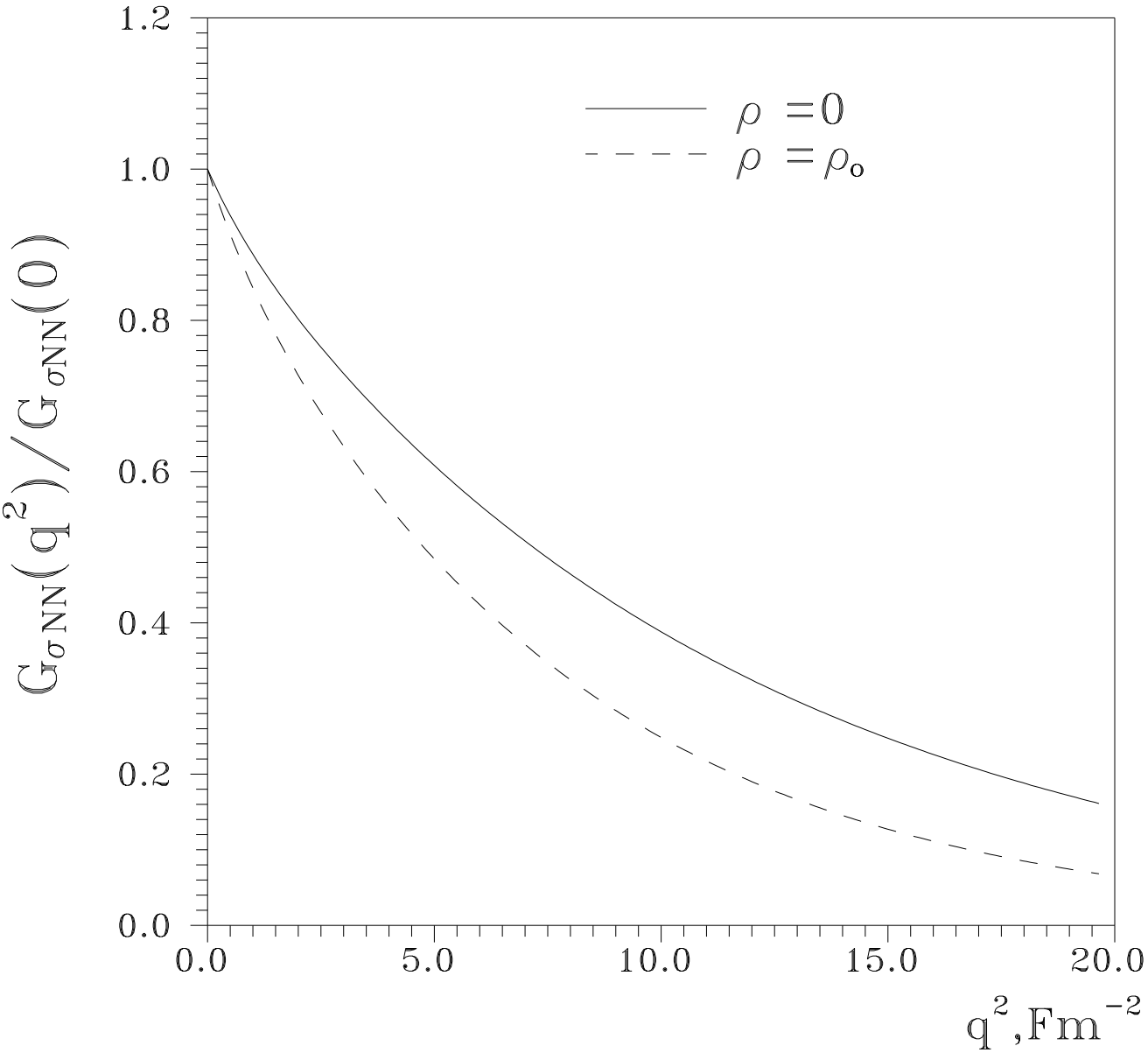
$\rho = \rho_o$
$G_{\pi NN}(q^2)/G_{\pi NN}(0)$
q^2,Fm^{-2}

Fig. 1.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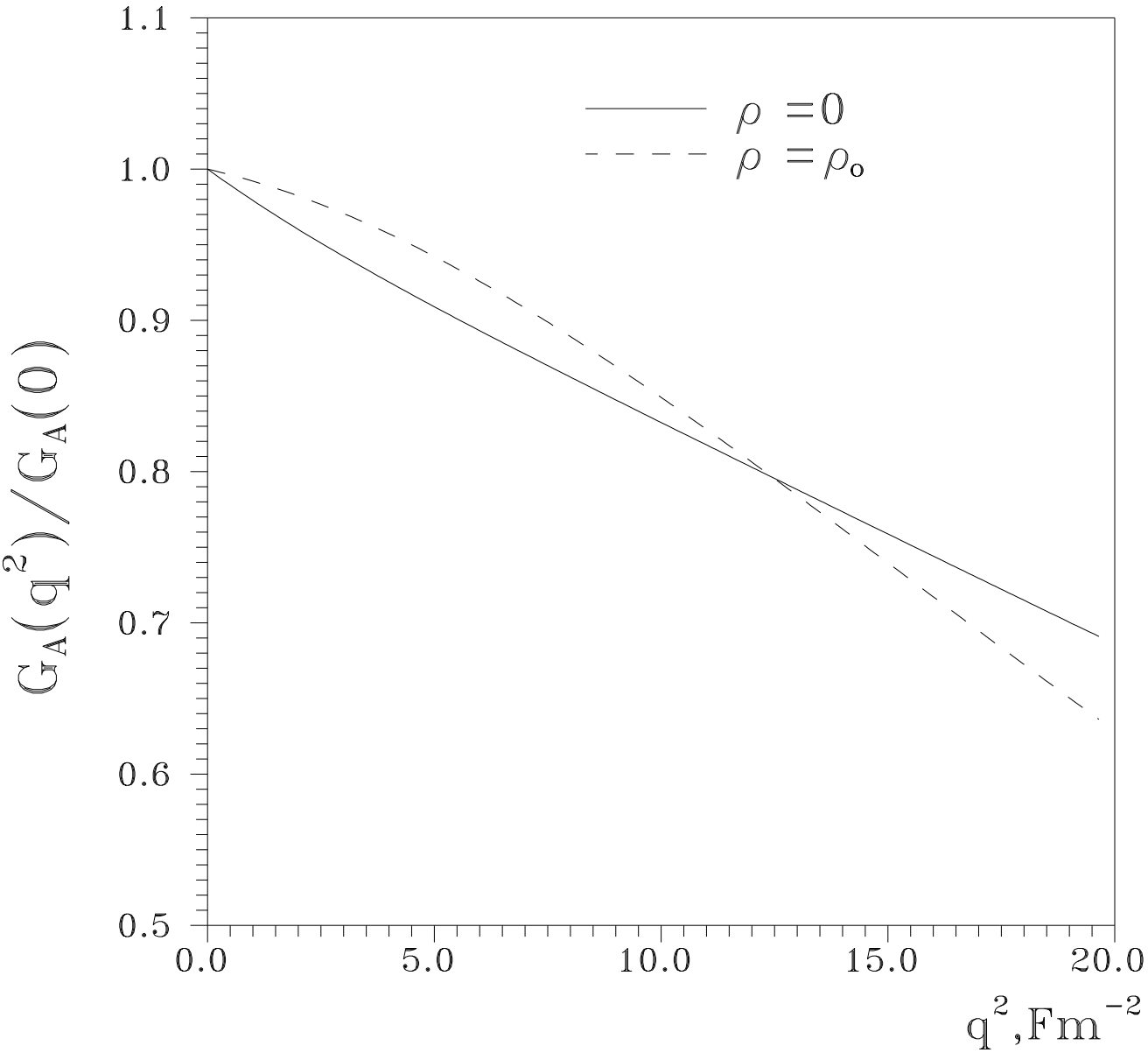
5.0
10.0
15.0
20.0
$G_{\sigma NN}(q^2)/G_{\sigma NN}(0)$
q^2,Fm^{-2}
$\rho = 0$
$\rho = \rho_o$

Fig.2.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0.8
0.7
0.6
0.5
0.0
5.0
10.0
15.0
20.0
$G_A(q^2)/G_A(0)$
q^2,Fm^{-2}
$\rho = 0$
$\rho = \rho_o$

Fig.3.

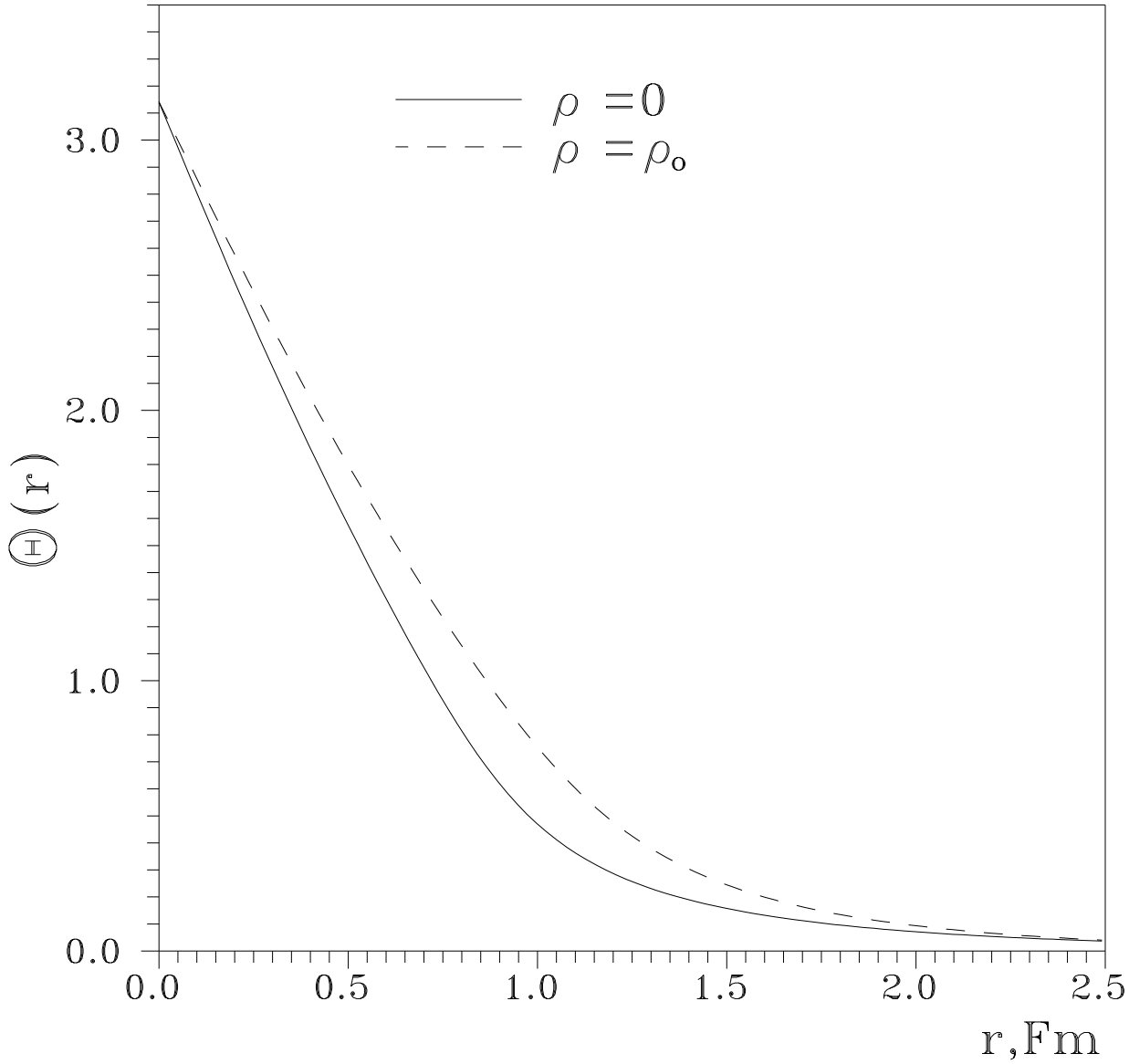

Fig.4a.

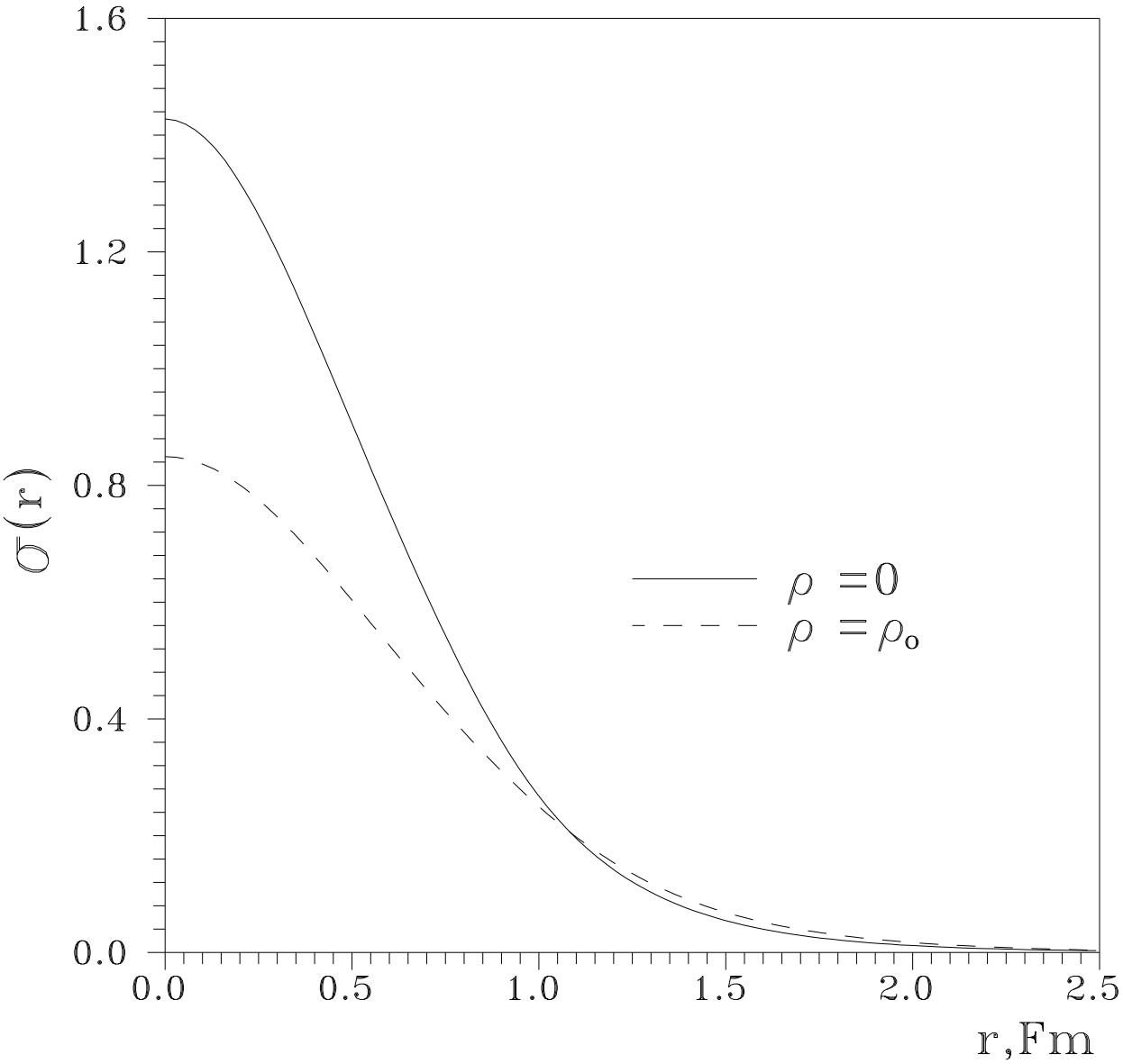

Fig.4b.